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Single Spin Asymmetry in Heavy Flavor Photoproduction as a Test of pQCD

(Revised version)

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We analyze in the framework of pQCD the properties of the single spin asymmetry in heavy flavor production by linearly polarized photons. At leading order, the parallel- perpendicular asymmetry in azimuthal distributions of both charm and bottom quark is predicted to be about 20% in a wide region of initial energy. Our analysis shows that the next-to-leading order corrections practically do not affect the Born predictions for the azimuthal asymmetry at energies of the fixed target experiments. Both leading and next-to-leading order predictions for the asymmetry are insensitive to within few percent to theoretical uncertainties in the QCD input parameters: m_Q, μ_R, μ_F, Λ_{QCD} and in the gluon distribution function. We estimate also nonperturbative contributions to azimuthal distributions due to the gluon transverse motion in the target and the final quark fragmentation. Our calculations show that nonperturbative corrections to a B-meson azimuthal asymmetry are negligible. We conclude that measurements of the single spin asymmetry would provide a good test of pQCD applicability to heavy flavor production at fixed target energies.

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I. INTRODUCTION

In the framework of perturbative QCD, the basic spin-averaged characteristics of heavy flavor hadro-, photo- and electroproduction are calculated up to the next-to-leading order (NLO) [1–8]. During the last ten years, these NLO results have been widely used for a phenomenological description of available data (for a review see [9]). At the same time, the key question still remains open: How to test the applicability of QCD at fixed order to the heavy quark production? On the one hand, the NLO corrections are large; they increase the leading order (LO) predictions for both charm and bottom production cross sections approximately by a factor of 2. For this reason, one could expect that the higher order corrections as well as the nonperturbative contributions can be essential in these processes, especially for the c-quark case. On the other hand, it is very difficult to compare directly, without additional assumptions, the pQCD predictions for spin-averaged cross sections with experimental data because of a high sensivity of the theoretical calculations to standard uncertainties in the input QCD parameters. The total uncertainties associated with the unknown values of the heavy quark mass, m_Q, the factorization and renormalization scales, μ_F and μ_R, Λ_{QCD} and the parton distribution functions are so large that one can only estimate the order of magnitude of the pQCD predictions for total cross sections [7,8]. In particular, at the energies of the fixed target experiments the theoretical calculations are especially sensitive to the value of the heavy quark mass which plays the role of a cutoff parameter for infrared singularities of the theory. For the shapes of the one- and two-particle differential distributions the above uncertainties are moderate in comparison with the ones for total cross sections; however they are also significant. In fact these uncertainties are of the same order as the contributions of nonperturbative effects (such as the primordial transverse motion of incoming partons and the hadronization phenomena) which are usually used for a phenomenological description of the charm and bottom differential spectra [9,10].

Since the spin-averaged characteristics of heavy flavor production are not well defined quantitatively in pQCD it is of special interest to study those spin-dependent observables which are stable under variations of input parameters of the theory. In this paper we analyze the charm and bottom production by linearly polarized photons, namely the reactions

$$\gamma \uparrow + N \to Q(\overline{Q}) + X. \tag{1.1}$$

In particular, we calculate the single spin asymmetry parameter, $A(s)$, which measures the parallel-perpendicular asymmetry in the quark azimuthal distribution:

$$A(s) = \frac{1}{\mathcal{P}_\gamma} \frac{\mathrm{d}\sigma(s, \varphi = 0) - \mathrm{d}\sigma(s, \varphi = \pi/2)}{\mathrm{d}\sigma(s, \varphi = 0) + \mathrm{d}\sigma(s, \varphi = \pi/2)}. \tag{1.2}$$

Here $\mathrm{d}\sigma(s,\varphi) \equiv \frac{\mathrm{d}\sigma}{\mathrm{d}\varphi}(s,\varphi)$, $\mathcal{P}_\gamma$ is the degree of linear polarization of the incident photon beam, $\sqrt{s}$ is the centre of mass energy of the process (1.1) and φ is the angle between the beam polarization direction and the observed quark transverse momentum. The main results of our analysis can be formulated as follows:

-At fixed target energies, the LO predictions for azimuthal asymmetry (1.2) are not small and can be tested experimentally. For instance,

$$A(s = 400\ \mathrm{GeV}^2)\ |^{\mathrm{LO}}_{\mathrm{Charm}} \approx A(s = 400\ \mathrm{GeV}^2)\ |^{\mathrm{LO}}_{\mathrm{Bottom}} \approx 0.18. \tag{1.3}$$

-The NLO corrections, both real and virtual, practically do not affect the Born predictions for $A(s)$ at fixed target energies.

-At energies sufficiently above the production threshold, both leading and next-to-leading order predictions for $A(s)$ are insensitive (to within few percent) to uncertainties in the QCD parameters: m_Q, μ_R, μ_F, Λ_{QCD} and in the gluon distribution function. This implies that theoretical uncertainties in the spin-dependent and spin-averaged cross sections (the numerator and denominator of the fraction (1.2), respectively) cancel each other with a good accuracy.

Our analysis shows that the p_T- and x_F-spectra of the single spin asymmetry also depend weekly on the variations of QCD parameters. To be specific: Theoretical uncertainties in the pQCD predictions for the azimuthal asymmetry differential distribution are always significantly smaller than the ones in calculations of the shape of the corresponding spectrum of unpolarized cross section.

We conclude that the single spin asymmetry is an observable quantitatively well defined and rapidly convergent in pQCD. Measurements of asymmetry parameters would provide a good test of the fixed order QCD applicability to charm and bottom production.

Another important question is how the fixed order predictions for asymmetry parameters are affected by non-perturbative contributions usually used for the description of unpolarized spectra. We estimate the nonperturbative corrections to $A(s)$ due to the transverse motion of partons in the target. For this purpose we use a parametrization of the intrinsic transverse momentum distribution proposed in ref. [10] (so-called k_T-kick). It is shown that the k_T-kick corrections to the b-quark azimuthal asymmetry $A(s)$ are negligible. Because of the smallness of the c-quark mass, the k_T-kick corrections to $A(s)$ in the charm case are larger; they are of order of 20%.

Modeling nonperturbative effects with the help of the k_T-kick and the Peterson fragmentation function we analyze also the p_T- and x_F -behavior of azimuthal asymmetry in D- and B-meson photoproduction. It is shown that for the B-meson both the k_T-kick and the fragmentation contributions are small almost in the whole region of kinematical variables p_T and x_F. For the D-meson, the k_T-kick corrections are essential at low values of p_T, $p_T \lesssim m_c$, and rapidly vanish at $p_T > m_c$.

The paper is organized as follows. In Sect.II we analyze the properties of heavy quark azimuthal distributions at leading order. We also give the physical explanation of the fact that the pQCD predictions for $A(s)$ are approximately the same at LO and at NLO. The details of our calculations of radiative corrections are too long to be presented in this paper; they will be reported separately in a forthcoming publication [11]. In Sect.III we discuss the nonperturbative contributions caused by both k_T-kick and Peterson fragmentation mechanisms. A comparison of the QCD predictions with the Regge model ones is also given.

II. SINGLE SPIN ASYMMETRY IN PQCD

A. Leading order predictions

At leading order, $\mathcal{O}(\alpha_{em}\alpha_S)$, the only partonic subprocess which is responsible for heavy quark photoproduction is the two-body photon-gluon fusion:

$$\gamma(k_\gamma) + g(k_g) \rightarrow Q(p_Q) + \overline{Q}(p_{\bar{Q}}). \tag{2.1}$$

The cross section corresponding to the Born diagrams (see Fig.1) is:

$$\frac{\mathrm{d}^2\hat{\sigma}}{\mathrm{d}\hat{x}\mathrm{d}\varphi}(\hat{s}, \hat{t}, \varphi, \mu_R^2) = C\frac{e_Q^2 \alpha_{em} \alpha_S(\mu_R^2)}{\hat{s}} \left[\frac{1+\hat{x}^2}{1-\hat{x}^2} + \frac{2(1-\beta^2)(\beta^2-\hat{x}^2)}{(1-\hat{x}^2)^2}\left(1+\mathcal{P}_\gamma \cos 2\varphi\right)\right], \tag{2.2}$$

where $\mathcal{P}_\gamma$ is the degree of the photon beam polarization; φ is the angle between the observed quark transverse momentum, $\vec{p}_{Q,T}$, and the beam polarization direction. In (2.2) C is the color factor, $C = T_F = \mathrm{Tr}(T^a T^a)/(N_c^2 - 1) = 1/2$, and e_Q is the quark charge in units of electromagnetic coupling constant. We use the following definition of partonic kinematical variables:

$$\begin{aligned} &\hat{s} = (k_\gamma + k_g)^2; && \hat{t} = (k_\gamma - p_Q)^2; \\ &\hat{u} = (k_g - p_Q)^2; && \hat{x} = 1 + 2\frac{\hat{t} - m_Q^2}{\hat{s}}; \\ &\beta = \sqrt{1 - \frac{4m_Q^2}{\hat{s}}}; && \vec{p}_{Q,T}^{\,2} = \frac{\hat{s}}{4}\left(\beta^2 - \hat{x}^2\right). \end{aligned} \tag{2.3}$$

In the Born approximation, the invariant cross section of the single inclusive hadronic process,

$$\gamma(k_\gamma) + N(k_N) \rightarrow Q(p_Q) + X(p_X), \tag{2.4}$$

can be written in the form

$$\frac{E_Q \mathrm{d}^3\sigma}{\mathrm{d}^3 p_Q}(s, t, u, \varphi) = \int \mathrm{d}z \delta\left(\hat{s} + \hat{t} + \hat{u} - 2m_Q^2\right) g\left(z, \mu_F^2\right) \frac{2\hat{s}\mathrm{d}^2\hat{\sigma}}{\mathrm{d}\hat{t}\mathrm{d}\varphi}\left(\hat{s}, \hat{t}, \varphi, \mu_R^2\right). \tag{2.5}$$

Here $g\left(z, \mu_F^2\right)$ describes the gluon density in a nucleon N evaluated at a factorization scale μ_F. The hadronic variables are related to the partonic ones as follows:

$$\begin{aligned} &s = (k_\gamma + k_N)^2 = \hat{s}/z; && u = (k_N - p_Q)^2 = \hat{u}/z - m_Q^2\left(1/z - 1\right); \\ &t = (k_\gamma - p_Q)^2 = \hat{t}. \end{aligned} \tag{2.6}$$

In this paper we will discuss photoproduction processes only at fixed target energies. For this reason we do not take into account the contribution of so-called hadronic or resolved component of the photon. This contribution is small at the energies under consideration [7].

To analyze the azimuthal distributions in photoproduction, it is convenient to use the parallel-perpendicular asymmetry parameters. Apart from the quantity $A(s)$ defined by (1.2), we will consider also the parameters $A^p\left(p_T^2\right)$ and $A^x\left(x_F\right)$,

$$A^p(p_T^2) = \frac{1}{\mathcal{P}_\gamma}\frac{\mathrm{d}^2\sigma(s, p_T^2, \varphi=0) - \mathrm{d}^2\sigma(s, p_T^2, \varphi=\pi/2)}{\mathrm{d}^2\sigma(s, p_T^2, \varphi=0) + \mathrm{d}^2\sigma(s, p_T^2, \varphi=\pi/2)}, \tag{2.7}$$

$$A^x(x_F) = \frac{1}{\mathcal{P}_\gamma}\frac{\mathrm{d}^2\sigma(s, x_F, \varphi=0) - \mathrm{d}^2\sigma(s, x_F, \varphi=\pi/2)}{\mathrm{d}^2\sigma(s, x_F, \varphi=0) + \mathrm{d}^2\sigma(s, x_F, \varphi=\pi/2)}, \tag{2.8}$$

which describe the dependence of azimuthal asymmetry on the transverse momentum, $p_T^2 \equiv \vec{p}_{Q,T}^{\,2}$, and on the Feynman variable, $x_F = p_l/p_{l,\max}$, of observed particle, respectively. The quantities $\mathrm{d}^2\sigma(s, p_T^2, \varphi)$ and $\mathrm{d}^2\sigma(s, x_F, \varphi)$ are the cross section (2.5) integrated over x_F and over p_T^2, respectively. The quantity $\mathrm{d}\sigma(s, \varphi)$ in (1.2) corresponds to the cross section (2.5) integrated over both x_F and p_T^2.

Unless otherwise stated, the CTEQ3M [12] parametrization of the gluon distribution function is used. The default values of the charm and bottom mass are $m_c = 1.5$ GeV and $m_b = 4.75$ GeV; $\Lambda_4 = 300$ MeV and $\Lambda_5 = 200$ MeV. The default values of the factorization scale μ_F chosen for the $A(s)$ asymmetry calculation are $\mu_F \mid_{\text{Charm}} = 2m_c$ for the case of charm production and $\mu_F \mid_{\text{Bottom}} = m_b$ for the bottom case [9,10]. Calculating the p_T- and x_F -dependent

asymmetries $A^p\left(p_T^2\right)$ and $A^x\left(x_F\right)$, we use $\mu_F\mid^{p,x}_{\rm Charm}=2\sqrt{m_c^2+p_T^2}$ for charm and $\mu_F\mid^{p,x}_{\rm Bottom}=\sqrt{m_b^2+p_T^2}$ for bottom. For the renormalization scale, μ_R, we use $\mu_R=\mu_F$.

Let us discuss the pQCD predictions for the asymmetry parameters defined by (1.2), (2.7) and (2.8). Our calculations of $A(s)$ at LO for the c- and b-quark are presented by solid lines in Fig.2 and Fig.3, respectively. One can see that at energies sufficiently above the production threshold the single spin asymmetry $A(E_\gamma)$ depends weekly on E_γ, $E_\gamma=(s-m_N^2)/2m_N$.

The most interesting feature of LO predictions for $A(E_\gamma)$ is that they are practically insensitive to uncertainties in QCD parameters. In particular, changes of the charm quark mass in the interval $1.2<m_c<1.8$ GeV affect the quantity $A(E_\gamma)$ by less than 6% at energies $40<E_\gamma<1000$ GeV. Remember that analogous changes of m_c lead to variations of total cross sections from a factor of 10 at $E_\gamma=40$ GeV to a factor of 3 at $E_\gamma=1$ TeV. The extreme choices $m_b=4.5$ and $m_b=5$ GeV lead to 3% variations of the parameter $A(E_\gamma)$ in the case of bottom production at energies $250<E_\gamma<1000$ GeV. The total cross sections in this case vary from a factor of 3 at $E_\gamma=250$ GeV to a factor of 1.5 at $E_\gamma=1$ TeV. The changes of $A(E_\gamma)$ are less than 3% for choices of μ_F in the range $\frac{1}{2}m_b<\mu_F<2m_b$. For the total cross sections, such changes of μ_F lead to a factor of 2.7 at $E_\gamma=250$ GeV and of 1.7 at $E_\gamma=1$ TeV. We have verified also that all the CTEQ3 versions of the gluon distribution function [12] as well as the CMKT parametrization [13] lead to asymmetry predictions which coincide with each other with accuracy better than 1.5% [1].

In the Born approximation scaling holds: with a good accuracy the quantity $A(s)$ is a function of the variable η, $\eta=4m_Q^2/s$, so that

$$A(s)\mid^{\rm LO}_{\rm Bottom}\approx A(\frac{m_c^2}{m_b^2}s)\mid^{\rm LO}_{\rm Charm}. \tag{2.9}$$

The scaling behavior of $A(\eta)$ (i.e. its independence of Λ_{QCD}/m_Q) is demonstrated in Fig.4[2].

In Fig.5/Fig.6 we show by a solid line the LO predictions for the p_T^2-/p_T-dependent parameter $A^p\left(p_T^2\right)/A^p\left(p_T\right)$ describing the azimuthal asymmetry in charm/bottom production. p_T-distributions grow rapidly with p_T up to $p_T\approx m_Q$ and fall slowly as p_T becomes larger than the heavy quark mass. The dependence of p_T-spectra on variations of m_Q is shown in Fig.7 and Fig.8. One can see that, contrary to $A(s)$, the form of the p_T^2-spectrum is sensitive to the value of charm quark mass. Note however that variations of the $A^p\left(p_T^2\right)$ shape due to changes of m_c are significantly smaller than the corresponding ones for the unpolarized distribution $\frac{{\rm d}\sigma}{{\rm d}p_T^2}(s,p_T^2)$ [9]. We have also verified that a change in the other input parameters has practically no effect on the computed values of $A^p\left(p_T^2\right)$ for both charm and bottom.

In the Born approximation the p_T-distribution of azimithal asymmetry is practically a function of two variables: $\eta=4m_Q^2/s$ and $\xi=p_T^2/m_Q^2$. The function $A^p\left(\xi\right)$ at different values of η is shown in Fig.9.

We have calculated also the dependence of single spin asymmetry on x_F. The LO predictions for $A^x\left(x_F\right)$ defined by (2.8) in the case of c- and b-quark production are presented by solid lines in Fig.10 and Fig.11, respectively. x_F-distributions take their maximal values approximatelly at $x_F\approx 0.5$ and fall to zero as $x_F\rightarrow 1$.

B. Radiative corrections

Let us briefly discuss the NLO corrections to the single spin asymmetry $A(s)$. It is well known that, at order $\mathcal{O}(\alpha_{em}\alpha_S^2)$, the main heavy quark photoproduction mechanism is the real gluon emission in the photon-gluon fusion:

$$\gamma(k_\gamma)+g(k_g)\rightarrow Q(p_Q)+\overline{Q}(p_{\overline{Q}})+g(p_g). \tag{2.10}$$

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[1]Note however that the fixed order predictions for azimuthal asymmetry are insensitive to uncertainties in QCD parameters only at energies sufficiently above the production threshold. For instance, at $E_\gamma<10$ GeV, changes of the charm quark mass in the interval $1.2<m_c<1.8$ GeV lead to 100% variations of the QCD predictions for $A(s)$.

[2]Eq.(1.3) does not contradict to eq.(2.9). As one can see from Fig.4, the asymmetry parameter $A(\eta)$ is not a monotonic function of variable η. So, eq.(1.3) reflects only the fact that $A(\eta=0.25)\approx A(\eta=0.025)$.

According to the analysis [3,4], practically whole contribution to the heavy quark production in photon-hadron reactions at fixed target energies, $E_\gamma \lesssim 1$ TeV, originetes from the so-called initial-state gluon bremsstrahlung (ISGB) mechanism which is due to the Feynman diagrams with the t-channel gluon exchange (see Fig.12). Since the gluon distribution function increases very steeply at small z, $g(z) \propto 1/z$, the order-α_S^2 photon-hadron cross section is determined at $E_\gamma \lesssim 1$ TeV by the threshold, $\hat{s} \sim 4m_Q^2$, behavior of the γg cross section. Near the threshold, a large logarithmic enhancement of the t-channel gluon exchange diagrams contribution takes place in the collinear, $\vec{p}_{g,T} \to 0$, and soft, $\vec{p}_g \to 0$, limits [3,4]. Effectively, the ISGB contribution is proportional to the Born γg differential cross section:

$$\frac{\mathrm{d}\hat{\sigma}^{\mathrm{ISGB}}}{\mathrm{d}\hat{t}}\left(\hat{s},\hat{t}\right) \approx \frac{\alpha_S}{\pi} K\left(\hat{s}\right) \frac{\mathrm{d}\hat{\sigma}^{\mathrm{LO}}}{\mathrm{d}\hat{t}}\left(\hat{s},\hat{t}\right), \qquad \hat{s} \sim 4m_Q^2, \tag{2.11}$$

where $K\left(\hat{s}\right)$ is an enhancement factor.

Since the azimuthal angle φ is the same for both γg and $Q\overline{Q}$ centre of mass systems in the collinear and soft limits, it seems natural to expect that the eq.(2.11) can be generalized to the spin-dependent case substituting the spin-averaged cross sections in (2.11) by the φ-dependent ones. Indeed, the threshold enhancement of the ISGB mechanism is due to the gluon propagator pole in the diagrams in Fig.12 which is a common factor for both spin-dependent and spin-independent amplitudes.

It is well known that the shapes of differential cross sections of heavy quark production in photon-hadron reactions are not sensitive to radiative corrections [3,4]. For instance, the normalized quantity

$$f\left(s,p_T^2\right) = \frac{1}{\sigma_{int}(s)} \frac{\mathrm{d}\sigma}{\mathrm{d}p_T^2}\left(s,p_T^2\right), \tag{2.12}$$

where $\sigma_{int}(s) = \int \mathrm{d}p_T^2 \frac{\mathrm{d}\sigma}{\mathrm{d}p_T^2}(s,p_T^2)$ and $p_T^2 \equiv \vec{p}_{Q,T}^{\,2}$, is practically the same at LO and at NLO. This fact means that non-small contributions of the enhancement factor $K\left(\hat{s}\right)$ (NLO corrections) to the p_T-dependent and to the p_T-integrated photon-hadron cross sections, $\mathrm{d}\sigma^{\mathrm{NLO}}(s,p_T^2) \approx \int \mathrm{d}z g(z) \mathrm{d}\sigma^{\mathrm{ISGB}}(zs,p_T^2)$, cancel each other in the ratio (2.12) with a good accuracy. One can assume that the same situation takes place also for the single spin asymmetry which is a ratio of the φ-dependent cross section to the φ-averaged one.

Our calculations show that it is really the case. Radiative corrections, both real and virtual, to the photon-gluon fusion mechanism practically do not affect the Born predictions for the single spin asymmetry in heavy flavor photoproduction at fixed target energies. Moreover the azimuthal asymmetry is independent (to within few percent) of the theoretical uncertainties in the QCD input parameters (m_Q, μ_R, μ_F and Λ_{QCD}) at NLO too. The details of our NLO analysis are too long to be presented here and will be given in a separate publication [11].

As to the photon-quark fusion, $\gamma q \to Q\overline{Q}q$, the dominant production mechanism in this reaction is the so-called flavor exitation (FE), also arising from the diagrams with the $t-$channel gluon exchange in Fig.12. However the contribution of the FE mechanism may be essential at superhigh energies only [4]. For instance, the contribution of the γq reactions to the unpolarized bottom photoproduction makes only 5-10% from the contribution of the γg processes at $E_\gamma \lesssim 1$ TeV. It is evident that an account of the photon-quark reactions cannot affect significantly the predictions of the photon-gluon fusion mechanism at fixed target energies in the polarized case too.

III. NONPERTURBATIVE CONTRIBUTIONS

Let us discuss how the pQCD predictions for single spin asymmetry are affected by nonperturbative contributions due to the intrinsic transverse motion of the gluon and the fragmentation of produced heavy quark. Because of the c-quark low mass, these contributions are especially important in the case of charmed particle production. In our analysis, we use the MNR model [10] parametrization of the gluon transverse momentum distribution,

$$\vec{k}_g = z\vec{k}_N + \vec{k}_{g,T}. \tag{3.1}$$

According to [10], the primordial transverse momentum, $\vec{k}_{g,T}$, has a random Gaussian distribution:

$$\frac{1}{N}\frac{\mathrm{d}^2N}{\mathrm{d}^2k_T} = \frac{1}{\pi\langle k_T^2\rangle}\exp\left(-\frac{k_T^2}{\langle k_T^2\rangle}\right), \tag{3.2}$$

where $k_T^2 \equiv \vec{k}_{g,T}^{\,2}$. It is evident that the inclusion of this effect results in a dilution of azimuthal asymmetry. In [9,10], the parametrization (3.2) (so-called k_T-kick) together with the Peterson fragmentation function [14],

$$D(y) = \frac{a_\varepsilon}{y\left[1 - 1/y - \varepsilon/(1-y)\right]^2} \tag{3.3}$$

(where a_ε is fixed by the condition $\int_0^1 \mathrm{d}y D(y) = 1$), have been used to describe the single inclusive spectra and the $Q\overline{Q}$ correlations in photo- and hadroproduction at NLO. It was shown that the available data on charm photoproduction allow to choose for the averaged intrinsic transverse momemtum, $\langle k_T^2\rangle$, any value between 0.5 and 2 GeV^2.

Our calculations of the parameter $A(s)$ at LO with the k_T-kick contributions are presented in Fig.2 and Fig.3 by dashed ($\langle k_T^2\rangle = 0.5$ GeV^2) and dotted ($\langle k_T^2\rangle = 1$ GeV^2) curves. One can see that in the c -quark case the k_T-kick reduces the value of $A(s)$ approximately by 15% at $\langle k_T^2\rangle = 0.5$ GeV^2 and by 20% at $\langle k_T^2\rangle = 1$ GeV^2. The k_T -kick corrections to the bottom asymmetry are systematically smaller; they do not exceed 5% for both $\langle k_T^2\rangle = 0.5$ GeV^2 and $\langle k_T^2\rangle = 1$ GeV^2.

Nonperturbative contributions to the p_T-dependent asymmetry parameters $A^p\left(p_T^2\right)$ and $A^p\left(p_T\right)$ are shown in Fig.5 and Fig.6. It is seen that the k_T-kick corrections decrease rapidly with the increase of the heavy quark transverse mass. For the B-meson, they are negligibly small in the whole region of p_T. In the case of a D -meson production, the k_T-kick corrections are essential only in the region of low $p_T \lesssim m_c$.

Calculating the hadronization effect contributions we use for the parameter ε that characterizes the Peterson fragmentation function the values $\varepsilon_D = 0.06$ for a D-meson and $\varepsilon_B = 0.006$ for a B-meson [15]. Strictly speaking, according to the factorization theorems, the application of the fragmentation function formalism can only be justified in the region of high p_T. It is seen from Fig.5 and Fig.6 that for $p_T > m_Q$ the account of the fragmentation function (3.3) leads to a reduction of the p_T-spectra. Fragmentation corrections to $A^p\left(p_T^2\right)$ are of order of 15% in the case of a charmed meson production; they are less than 5% for a B-meson case.

For completeness, in Fig.10 and Fig.11 we presented nonperturbative contributions to the x_F-distributions of single spin asymmetry. One can see that the k_T-kick corrections to $A^x(x_F)$ in the bottom case are small in the whole region of x_F. As expected, the x_F-distribution of the c-quark azimuthal asymmetry is more sensitive to the k_T-kick corrections.

So, we can conclude that nonperturbative corrections to the b-quark asymmetry parameters (1.2) and (2.7) due to the k_T-kick and Peterson fragmentation effects practically do not affect predictions of the underlying perturbative mechanism: photon-gluon fusion.

To illustrate how strongly the azimuthal distributions depend on the basic subprocess dynamics let us consider the mechanisms of the photon fusion with nonvector primordials. The latter can be nonperturbative, color or white objects (say, reggeons at $p_{\mathcal{O}}^2 \approx 0$). In the Born approximation, the partonic cross sections corresponding to the reactions

$$\gamma + \mathcal{O} \rightarrow Q + \overline{Q} \tag{3.4}$$

have the following form:

$$\frac{\mathrm{d}^2\hat{\sigma}^{\mathcal{O}=S}}{\mathrm{d}\hat{x}\mathrm{d}\varphi} = C\frac{e_Q^2\alpha_{em}\alpha_{QSQ}}{\hat{s}}\left[\frac{2}{1-\hat{x}^2} - \frac{4(1-\beta^2)(\beta^2-\hat{x}^2)}{(1-\hat{x}^2)^2}\left(1+\mathcal{P}_\gamma\cos 2\varphi\right)\right], \tag{3.5}$$

$$\frac{\mathrm{d}^2\hat{\sigma}^{\mathcal{O}=P}}{\mathrm{d}\hat{x}\mathrm{d}\varphi} = C\frac{e_Q^2\alpha_{em}\alpha_{QPQ}}{\hat{s}}\frac{2}{1-\hat{x}^2}, \tag{3.6}$$

where the cross sections $\hat{\sigma}^{\mathcal{O}=S}$ and $\hat{\sigma}^{\mathcal{O}=P}$ describe the photon fusion with a scalar ($\mathcal{O} = S$) and a pseudoscalar ($\mathcal{O} = P$) object, respectively. One can see from (2.2) and (3.5),(3.6) that only the gluon contribution leads to a positive azimuthal asymmetry. In the case of a scalar primordial, the asymmetry parameters are predicted to be negative. The photon fusion with a pseudoscalar object (say, π^0-meson) leads to an φ -independent cross section. Note that the expressions (3.5),(3.6) do not correspond to any concrete models; they are presented only as illustrative exercises demonstrating how the azimuthal distribution reflects the nature of the underlying subprocess.

Completing the Section let us compare the QCD predictions for a D-meson single spin asymmetry with the Regge pole model ones. In principle, at arbitrary values of variables x_F and p_T, the spin dependent part of a D-meson

photoproduction cross section can be of two types. The first, $|[\vec{e},\vec{n}_0]\vec{p}_T|^2 = \vec{p}_T^{\,2}\sin^2\varphi$, corresponds to the contribution of the t-channel exchanges with natural spin-parity while the second, $|(\vec{e}\vec{p}_T)|^2 = \vec{p}_T^{\,2}\cos^2\varphi$, describes the contribution of the t-channel singularities of unnatural spin-parity. In the above expressions, $\vec{e}$ is the polarization vector of the photon, $\vec{n}_0$ is a unit vector in the direction of the photon momentum and φ is the azimuthal angle of the D-meson momentum about $\vec{n}_0$: $\tan\varphi = ([\vec{e},\vec{n}_0]\vec{p}_T)/(\vec{e}\vec{p}_T)$. Really, the Regge pole model is only applicable in the narrow region $x_F \approx 1$ and $p_T^2 \ll s$ (so-called triple reggeon exchange limit). In this region, the cross section of the inclusive reaction is determined by the contribution of the leading (rightmost in the j-plane) Regge trajectory. The diagram, which describes the pseudoscalar meson photoproduction in the triple reggeon exchange limit, is sketched in Fig.13. Since the relevant leading Regge trajectory, α_{D^*}, is of natural spin-parity, the spin structure of the corresponding reggeon-particle vertex, $\gamma\alpha_{D^*}D$, is written as:

$$|\beta_{\gamma\alpha_{D^*}D}(p_T)|^2 \propto |[\vec{e},\vec{n}_0]\vec{p}_T|^2 = \frac{1}{2}\vec{p}_T^{\,2}\,(1-\cos 2\varphi)\,. \tag{3.7}$$

It is seen from (3.7) that, in contrast to QCD, the Regge model predicts in the region $x_F \approx 1$ a large negative azimuthal asymmetry such that $A^x(x_F)\,|^{\mathrm{Regge}} \rightarrow -1$ as $x_F \rightarrow 1$.

IV. CONCLUSION

In the investigation of mechanisms which are responsible for heavy flavor production at fixed target energies, the reactions (1.1) with a linearly polarized photon beam are of special interest. As it is shown in the present paper, the QCD LO predictions for the single spin asymmetry in both charm and bottom production are non-small and can be tested experimentally; in a wide region of initial energy the parameter $A(s)$ defined by (1.2) is of order of 20%. Our analysis shows that the NLO corrections practically do not affect the Born predictions for $A(s)$ at fixed target energies. Unlike the unpolarized cross section, the single spin asymmetry is an observable quantitatively well defined in QCD. In particular, at both LO and NLO, $A(s)$ is independent to within few percent of the theoretical uncertainties in m_Q, μ_R, μ_F, Λ_{QCD} and in the gluon distribution function. Our calculations show that the p_T- and x_F-distributions of the azimuthal asymmetry in bottom production are practically insensitive to nonperturbative contributions due to the primordial transverse motion and Peterson fragmentation effects.

So, the single spin asymmetry in heavy flavor production by linearly polarized photons is an observable quantitatively well defined, rapidly convergent and insensitive to nonperturbative contributions. Measurements of the azimuthal asymmetry in bottom production would be a good test of the conventional parton model based on pQCD.

Due to the c-quark low mass, nonperturbative contributions to the charm production can be essential. As it is shown in our paper, the pQCD and Regge approaches lead to strongly different predictions for the single spin asymmetry in the region of low p_T and $x_F \approx 1$. Data on the p_T- and x_F-distributions of the azimuthal asymmetry in D-meson production could make it possible to discriminate between these mechanisms.

Concerning the experimental aspects, the linearly polarized high energy photon beams can be generated using the Compton back-scattering of the laser light off the lepton beams (see, for instance, [16,17] and references therein). According to the above references, this method promises to provide the beams of real photons with a definite polarization and high monochromaticity.

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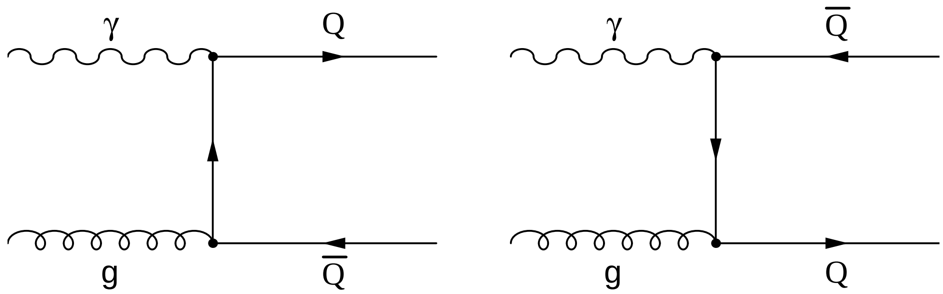

FIG. 1. Photon-gluon fusion diagrams at leading order.

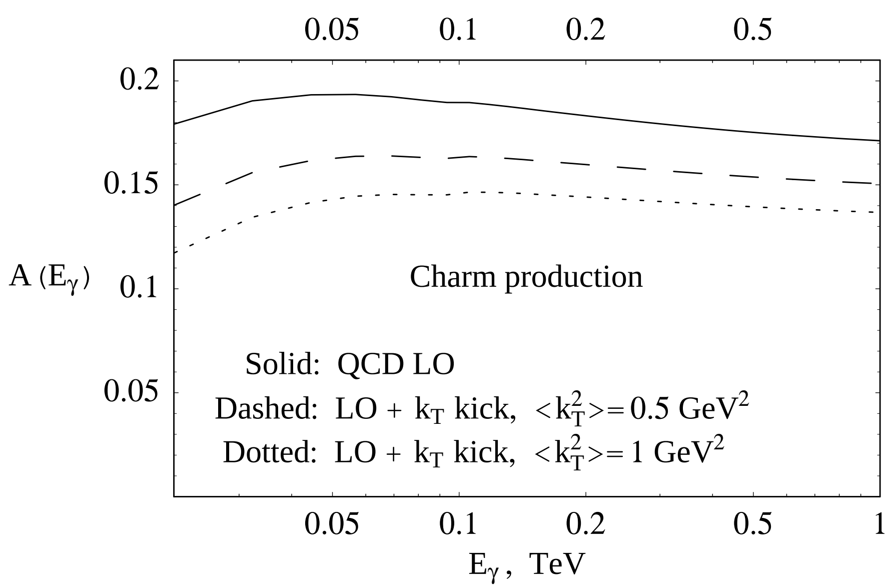

FIG. 2. Single spin asymmetry, $A(E_\gamma)$, in the c-quark production as a function of beam energy $E_\gamma = (s - m_N^2)/2m_N$; the QCD LO predictions with and without the inclusion of k_T-kick effect.

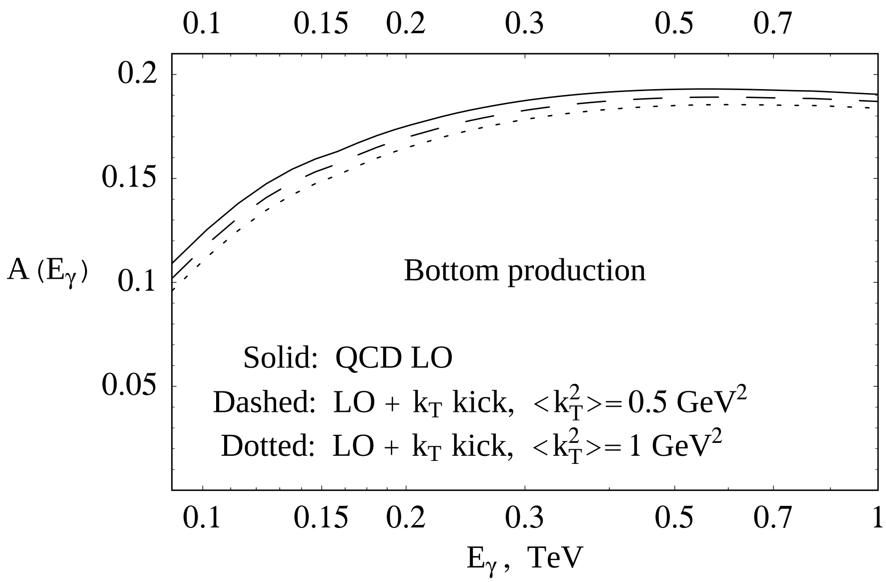

FIG. 3. The same as in Fig.2, but for the b-quark case.

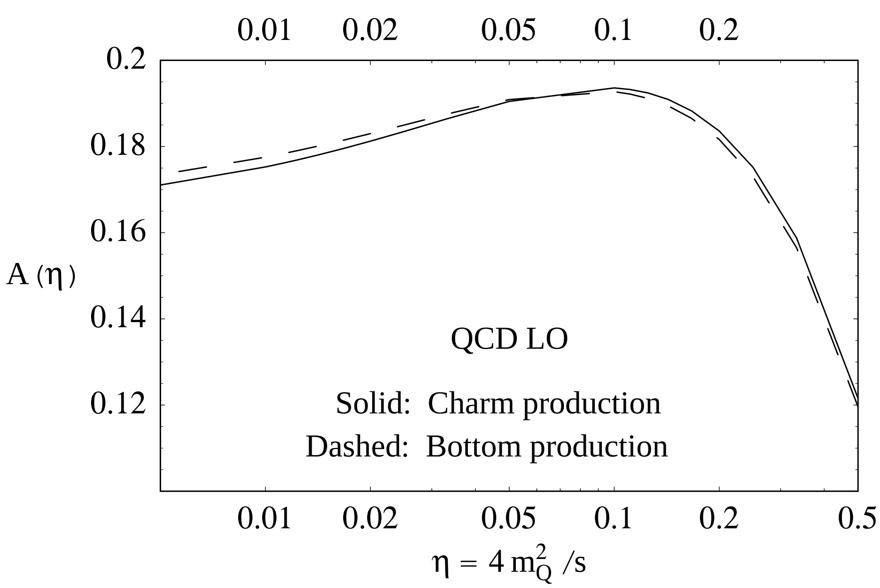

FIG. 4. Scaling behavior of the asymmetry parameter $A(\eta)$ as a function of $\eta = 4m_Q^2/s$ at QCD LO.

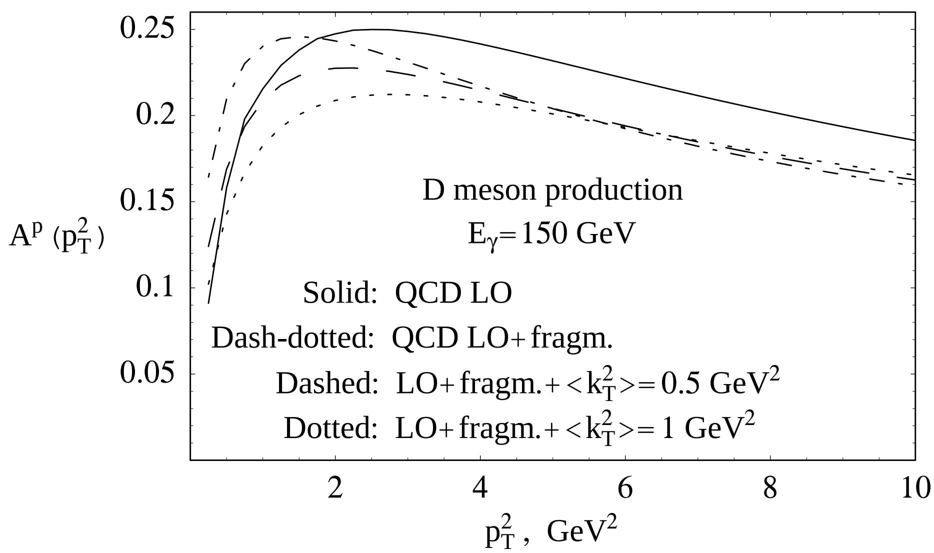

FIG. 5. p_T^2-distribution of azimuthal asymmetry, $A^p(p_T^2)$, in a D-meson production; the QCD LO predictions with and without the inclusion of the k_T-kick and Peterson fragmentation effects.

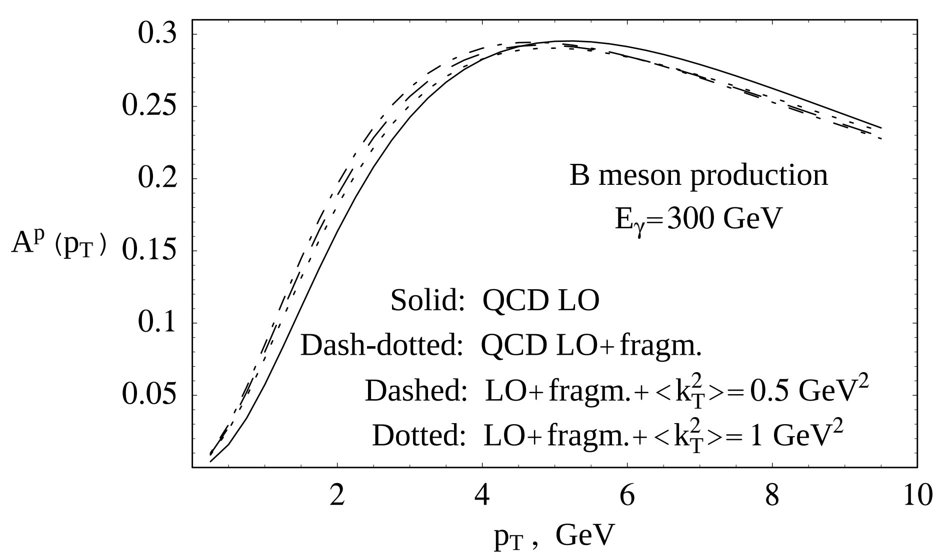

FIG. 6. The same as in Fig.5, but for the p_T-distribution of azimuthal asymmetry, $A^p(p_T)$, in a B-meson production.

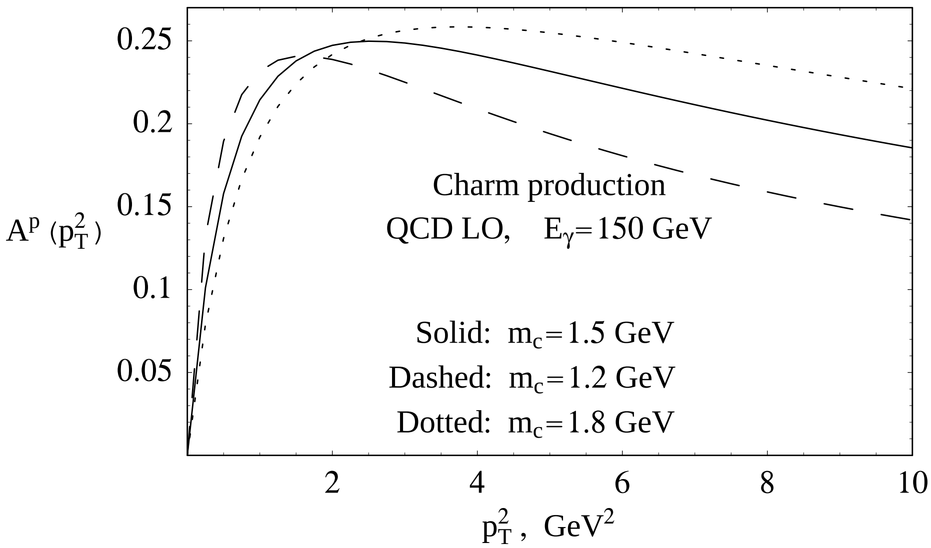

FIG. 7. Dependence of the p_T^2-spectrum, $A^p(p_T^2)$, on the c-quark mass, m_c, at QCD LO.

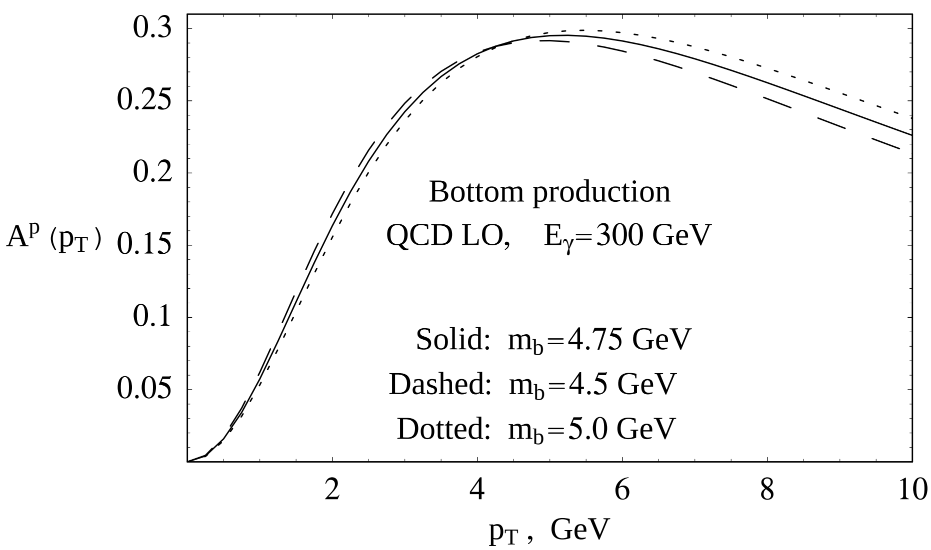

FIG. 8. Dependence of the p_T-spectrum, $A^p(p_T)$, on the b-quark mass, m_b, at QCD LO.

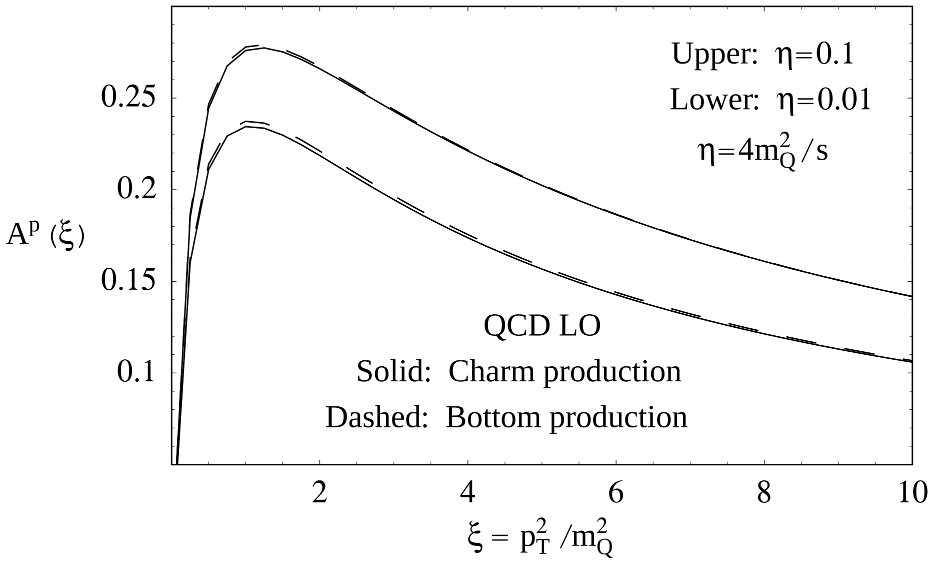

FIG. 9. Scaling behavior of the asymmetry parameter $A^p(\xi)$ as a function of ξ, $\xi = p_T^2/m_Q^2$, at different values of η at QCD LO.

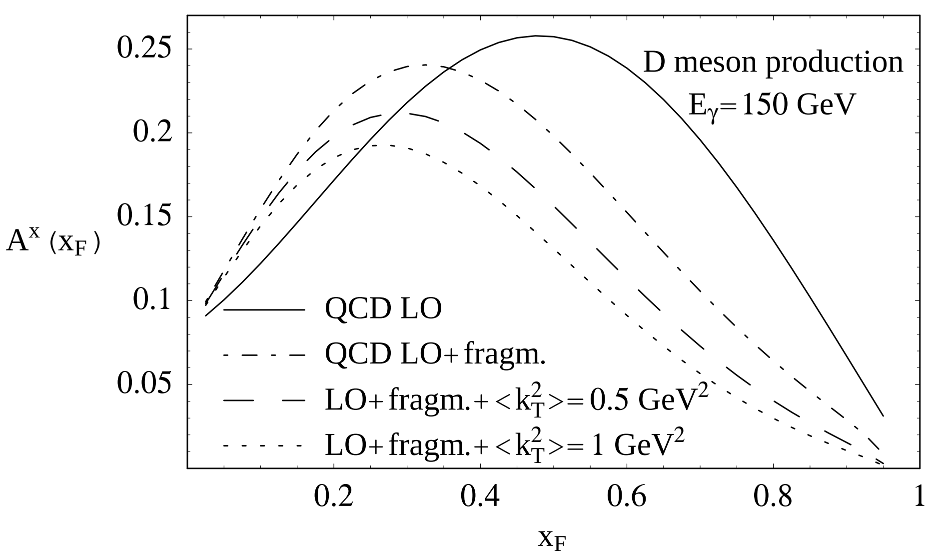

FIG. 10. x_F-distribution of the single spin asymmetry, $A^x(x_F)$, in a D-meson production; the QCD LO predictions with and without the inclusion of the k_T-kick and Peterson fragmentation effects.

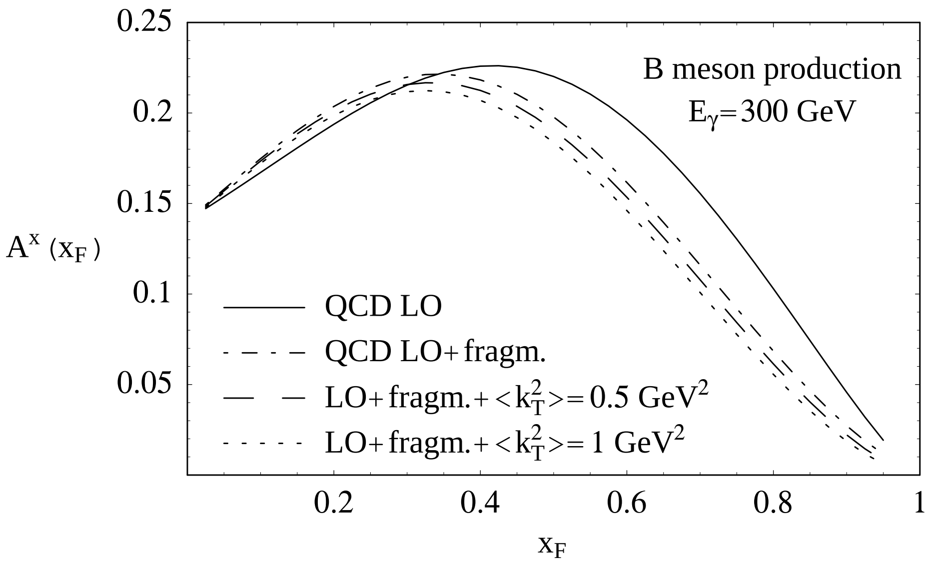

FIG. 11. The same as in Fig.10, but for the case of a B-meson production.

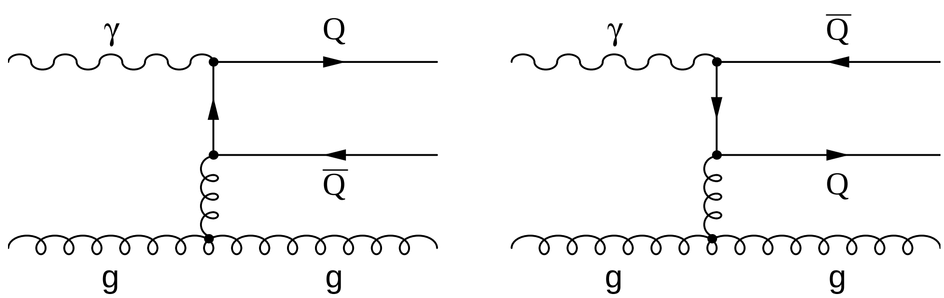

FIG. 12. t-channel gluon exchange diagrams in the photon-gluon fusion.

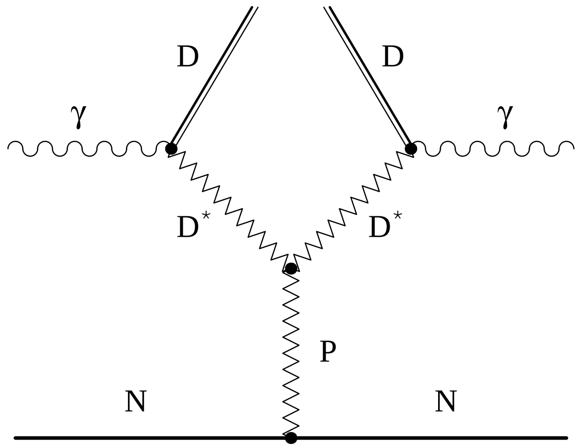

FIG. 13. Triple reggeon diagram for the process $\gamma N \to DX$.